

**Ar-Ar Thermochemistry of Apollo 12 Impact-Melt Breccia 12033,638-1.** C. A. Crow<sup>1</sup>, W. S. Cassata<sup>1</sup>, B. L. Jolliff<sup>2</sup>, R. A. Zeigler<sup>3</sup>, L. E. Borg<sup>1</sup>, and C. K. Shearer<sup>4</sup>, <sup>1</sup>Livermore National Laboratory, 7000 East Avenue (L-231), Livermore, CA 94550s (crow7@llnl.gov); <sup>2</sup>Washington University, St. Louis, MO; <sup>3</sup>NASA Johnson Space Center, Houston, TX; <sup>4</sup>University of New Mexico, Albuquerque, NM.

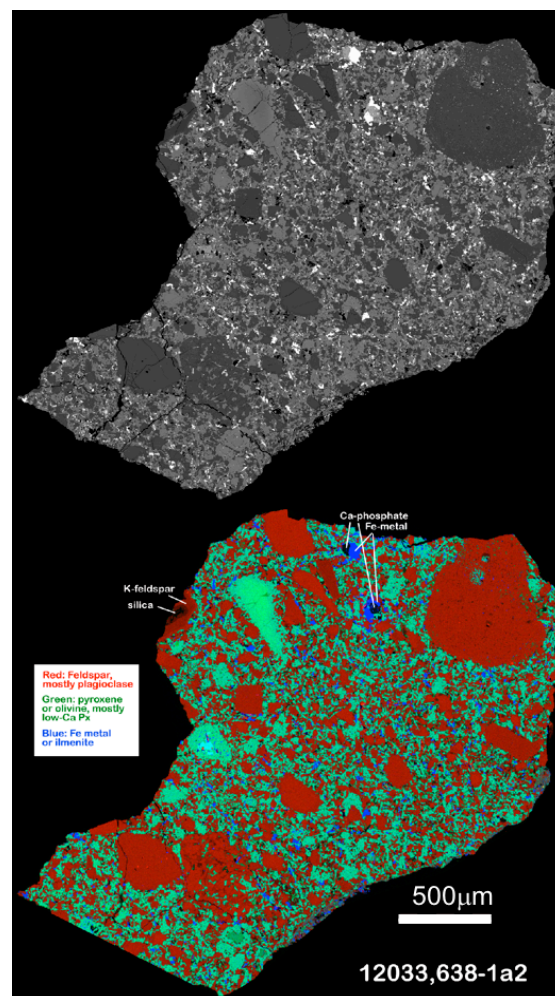
**Introduction:** We have undertaken an Ar-Ar thermochronology investigation as part of a coordinated multichronometer analysis of a single Apollo 12 impact-melt breccia to demonstrate the wide range of information that can be obtained for a single complex rock. This has implications for the age of formation, component makeup, and subsequent impact/shock and exposure history of the sample. This study also serves as a capabilities demonstration for the proposed MoonRise Mission [1]. The goal of this investigation is to elucidate the history of this sample through coordinated  $^{40}\text{Ar}/^{39}\text{Ar}$ , Sm-Nd, Rb-Sr and zircon  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages along with geochemical and petrographic context on a relatively small (~450 mg) sample. Here, we report preliminary results of the Ar-Ar thermochronology.

**Sample:** Apollo soil 12033 is characterized by high concentrations of KREEP-rich impact melt glass thought to be ejecta from the Copernicus impact event at ~800 Ma [2, 3, 4].  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology was conducted on a high-Th, mafic impact-melt breccia fragment separated from this soil sample, 12033,638-1 [5]. The average matrix grain size is 20-30  $\mu\text{m}$ , with occasional larger plagioclase grains and lithic clasts ranging between ~100  $\mu\text{m}$  to 1 mm (Figure 1) [5, 6]. Zircons identified in 12033 thin sections yield  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages between  $3888 \pm 25$  and  $4171 \pm 7$  Ma, which define a weighted average age of  $3920 \pm 13$  Ma [5].

**Analytical Procedures:** An aliquot of 12033,638-1 weighing 1.8 mg was co-irradiated with fluence monitors for 52 hours at the Oregon State University TRIGA reactor in the Cadmium-Lined In-Core Tube (CLICIT). Noble gas extractions were conducted in the Livermore Noble Gas Lab using temperature-controlled diode laser-heating following procedures similar to those described in [7]. Released gases were analyzed using a Nu Instrument *Noblesse* mass spectrometer equipped with six Faraday cup detectors and four ion-counting, discrete dynode multiplier detectors. Ages were calculated using the decay constants and standard calibration of [8].

### Results:

**Chronology.** The age spectrum obtained from 12033,638 (Figure 2c) defines a “young” average  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $939 \pm 86$  Ma ( $1\sigma$ ) over 74% of the released gas, with a minimum measured age of  $828 \pm 4$  Ma. These data are similar to other  $^{40}\text{Ar}/^{39}\text{Ar}$  ages obtained from Apollo 12 KREEP-rich glasses [2, 3, 4].

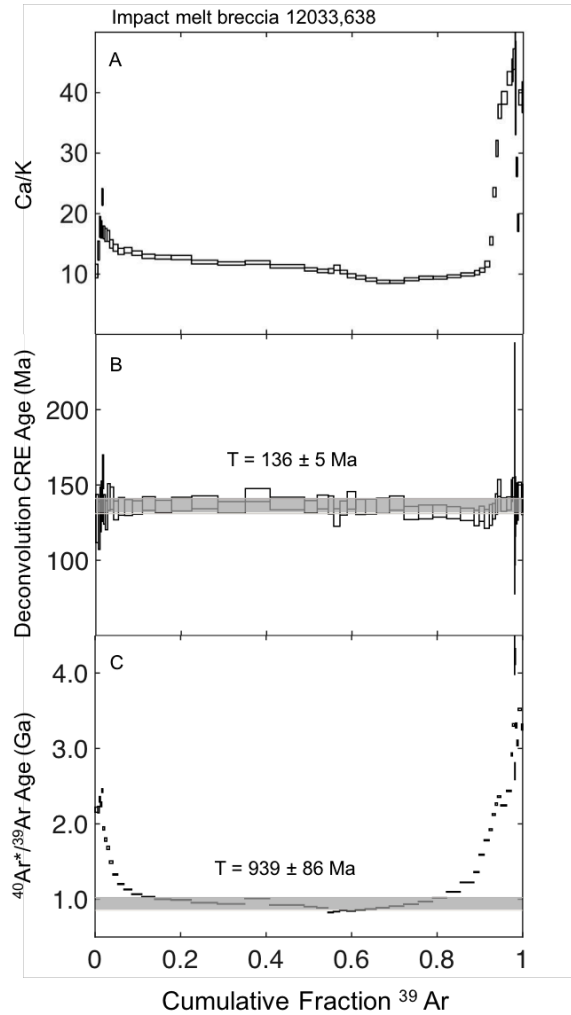


**Figure 1:** BSE image (top) of impact melt breccia 12033,638. EDS X-ray map (bottom) shows distribution of Al (red), Mg (green), and Fe (blue) corresponding to plagioclase, pyroxene/olivine and ilmenite or Fe metal respectively. [5, 6]

The higher  $^{40}\text{Ar}/^{39}\text{Ar}$  ratios observed in low temperature releases most likely reflect excess  $^{40}\text{Ar}$ , which have previously been reported in Apollo 12 soil samples [9].

High temperature releases have significantly older ages and likely reflect degassing of clasts and lithic fragments (based on the apparent Ca/K ratios; see Figure 2a). A maximum age of  $4177 \pm 102$  Ma is observed at high temperatures and represents a lower limit on the oldest clast ages. This age is older than the  $3920 \pm 13$  Ma age from [5], however it is within error

of the oldest concordant  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age of  $4171 \pm 7$  Ma.



**Figure 2:** Ca/K (A), CRE exposure age (B), and  $^{40}\text{Ar}^*/^{39}\text{Ar}$  age spectra (C) for impact-melt breccia 12033,638. The age spectrum defines a “young” average  $^{40}\text{Ar}^*/^{39}\text{Ar}$  age of  $939 \pm 86$  Ma. This suggests either (1) this is the age of impact melt crystallization or (2) extensive resetting occurred at this time. The average  $136 \pm 5$  Ma CRE exposure age implies the sample remained relatively shielded since excavation by the Copernicus impact at  $\sim 800$  Ma [2, 3, 4].

**Cosmic Ray Exposure Age.** Apparent cosmic ray exposure ages of each degassing step were calculated from the ratio of cosmogenic  $^{38}\text{Ar}$  ( $^{38}\text{Ar}_{\text{cos}}$ ) to reactor-produced  $^{37}\text{Ar}$  ( $^{37}\text{Ar}_{\text{Ca}}$ ) and  $^{39}\text{Ar}$  ( $^{39}\text{Ar}_{\text{K}}$ ) following procedures described in [10], using the  $^{38}\text{Ar}$  production rate from Ca of [11] and relative production rate from K of [12].

The cosmic ray exposure age spectrum is shown in Figure 2b and defines an average exposure age of  $136 \pm 5$  Ma ( $1\sigma$ ). Due to impact gardening, near-surface samples spend some time shallowly buried [10], where

production rates are lower than at the surface. The results in Fig 2B thus represent a lower limit on the near-surface residence time of 12033,638, as the exposure age is calculated using surface exposure production rates (i.e. no shielding corrections were applied). Thus, the 136 Ma exposure age indicates that 12033,638 has remained relatively shielded since its exhumation at  $\sim 900$  Ma, most likely as a result of the Copernicus impact event (refs from before). Measurements of un-irradiated fragments are underway.

**Discussion:** The agreement between the maximum  $^{40}\text{Ar}^*/^{39}\text{Ar}$  and  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages suggests that oldest clasts within 12033,638-1 date to at least  $4177 \pm 102$  Ma. The young  $^{40}\text{Ar}^*/^{39}\text{Ar}$  age observed over 74% of the released gas (minimum measured age of  $828 \pm 4$  Ma) suggests either (1) the formation age of the impact melt breccia is associated with the Copernicus impact event, or (2) extensive resetting of an older impact melt breccia occurred at that time. A similarly young,  $<1$  Ga, Pb-loss event was observed in discordant zircons from this sample [5]. Liu et al. [5] interpret the  $\sim 3.9$  Ga  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages of matrix hosted zircons as the matrix crystallization or breccia formation age. Alternatively, the  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages could reflect inherited ages of target rock or local zircons that were incorporated into the melt matrix. The  $\sim 800$ - $900$  Ma age could therefore represent the matrix crystallization age, at which time only large clasts retained ancient Ar components and the U-Pb system of small zircons was disturbed. Ultimately, combining multiple chronometers, along with modeling of ejecta conditions (efforts currently underway), will lead to a better understanding of the thermochronologic history of this complex sample.

#### References:

- [1] Jolliff B. L. et al. (2017) *LPSC XLVIII*, Abstract #1300.
- [2] Eberhardt P. et al. (1973) *The Moon*, 8, 104-114.
- [3] Bogard D. D. et al. (1994) *GCA*, 58, 3093-3100.
- [4] Barra F. et al. (2006) *GCA*, 70, 6016-6031.
- [5] Liu D. et al. (2012) *EPSL*, 319-320, 277-286.
- [6] Zeigler R. A. (2006) *LPSC XXXVII*, Abstract # 2366.
- [7] Cassata W.S. et al. (2010) *GCA*, 74, 6900-6920.
- [8] Renne P. R. (2011) *GCA*, 75, 5097-5100.
- [9] Poupeau G. (1972) *LPSC III*, 613-615.
- [10] Shuster D. L. and Cassata W. S. (2015) *GCA*, 155, 154-171.
- [11] Turner G. (1971) *EPSL*, 11, 227-234.
- [12] Eugster O. and Michel T. (1995) *GCA*, 59, 177-199.

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